

Pasture canopy temperature under cloudy humid conditions

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ABSTRACT

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The temperature of a forage canopy, which is determined primarily by climate conditions and plant water status, is an important regulator of the forage's physiological processes. Canopy temperature measurements are widely taken as an indicator of plant-water status under arid, sunny conditions. This study was conducted to determine the canopy temperature response of orchardgrass (*Dactylis glomerata* L.) to the high humidity and variable radiation levels of Appalachia. Average hourly climate parameters were measured along with average hourly canopy temperature and daily evapotranspiration from a monolith lysimeter at the North Appalachian Experimental Watershed at Coshocton, Ohio, from Day 110 through 183 of 1989. The responses during a reference spring with plentiful rainfall indicate that canopy temperature decreased 2.1°C for a 1 kPa increase in vapor pressure deficit and increased 0.6°C for each 100 W m⁻² increase in net radiation. The levels of average hourly wind during this period had no significant effect on canopy temperature. Aerodynamic and canopy resistances calculated from canopy temperature responses to vapor pressure deficit and net radiation were consistent except at net radiation levels below 100 W m⁻². Reductions in canopy height by a half, as a result of lodging, had no pronounced effect on evapotranspiration or canopy temperature. The response of canopy temperature to changes in climate conditions was as reliably determined under cloudy humid conditions as under sunny conditions.

INTRODUCTION

Jackson (1982), in his review of research on plant canopy temperature, noted that much of the early work was done in humid regions. This contributed to a common early historical misconception that leaves must always be above air temperature when in direct sun. High humidity suppresses evaporation from leaf stomata and, therefore, limits cooling. The relationship

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between air temperature and canopy temperature is now better understood, including conditions under which canopy temperature is below air temperature (Idso et al , 1981c, Paw U , 1984)

In the last two decades canopy temperature has been measured with infrared thermometers as a routine parameter to help determine evapotranspiration (ET) (Stone and Horten, 1974, Blad and Rosenberg, 1976, Hatfield et al , 1984) and plant water stress (Ehrler et al , 1978, Idso et al , 1981b, Jackson et al , 1981, Keener and Kircher, 1983, Clawson et al , 1989) This is of particular importance in arid and semi-arid regions where irrigation is an important and expensive agricultural management input

Canopy temperature has also been an important research tool for better understanding plant response to the environment Examples of this include, observing the hysteretic effect of evapotranspiration vs leaf-water potential in alfalfa during a diurnal cycle (Sharratt et al , 1983), assessing water stress in cotton due to high water tables (Reicosky et al , 1985) and determining the relative impact on evapotranspiration of soil heat flux compared with root conductance for soils of differing soil temperatures (Feldhake and Boyer, 1986)

In recent years the research lead for interpreting canopy temperature data in relation to environmental parameters has been in dry regions A major advance in our understanding was made with the development of a way to interpret the relation between canopy temperature and vapor pressure deficit (Idso et al , 1981a, Jackson et al , 1981, Idso, 1982) This relationship is subject to influence by wind and solar radiation (O'Toole and Hatfield, 1983, Hipps et al , 1985)

The important components of the energy budget can be described with the equation

$$R_n - G = H + \lambda E \quad (1)$$

where R_n is the net radiation (W m^{-2}), G is the soil heat flux (W m^{-2}), H is the sensible heat flux from the canopy to the air (W m^{-2}), and λE is the latent heat flux to the air (W m^{-2}) with λ being the heat of vaporization for water In studying the energy budgets of canopies it is frequently helpful to determine the efficiency with which energy is being transported in relation to climatic conditions Monteith (1963), utilized the concept of resistance to relate energy flow to driving potential Sensible heat can, therefore, be expressed as

$$H = \rho C(T_s - T_a)/r_{ah} \quad (2)$$

where ρ is the density of air (kg m^{-3}), C is the heat capacity of air ($\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), T_c is the canopy temperature ($^\circ\text{C}$), T_a is air temperature ($^\circ\text{C}$), and r_{ah} is the aerodynamic resistance to heat flow (s m^{-1}) Latent heat can also be expressed as

$$\lambda E = \rho \lambda \varepsilon (e^* - e_a)/P(r_{av} + r_c) \quad (3)$$

where ε is the ratio of the molecular weight of water to air, e^* is the saturated vapour pressure of air at the temperature of the canopy (Pa), e_a is ambient vapor pressure (Pa), P is atmospheric pressure (Pa), r_{av} is the aerodynamic resistance to vapor transport (s m^{-1}), and r_c is the resistance (s m^{-1}) which is owing to the ability of the canopy and soil to supply water for evaporation.

Instruments for determining canopy temperature by measuring emitted longwave infrared radiation are readily available, and as a result the difference between canopy temperature and air temperature is being exploited as a valuable indicator of energy partitioning between sensible and latent heat. Idso et al (1981a) and Idso (1982), showed an empirical linear relation between air-canopy temperature difference and vapour pressure deficit that was uniquely characteristic of the crop experiencing a high level of water availability. Jackson et al (1981) proposed, with analytical arguments, that this relation should be curvilinear. Idso and Clawson (1986) verified, with measurements, that the relation was curvilinear but that it was nearly linear under conditions of small vapor pressure deficits.

O'Toole and Real (1986), substituted the empirical relation between the air-canopy temperature difference into the analytical arguments in order to determine a canopy resistance and aerodynamic resistance for crops transpiring at the potential rate. These relations were expressed as

$$r_{ap} = \rho C_p a / R_n b (\Delta + 1/b) \quad (4)$$

and

$$r_{cp} = -r_{ap} [(\Delta + 1/b)/\Upsilon + 1] \quad (5)$$

where r_{ap} is aerodynamic resistance and r_{cp} canopy resistance for a canopy transpiring at the potential rate, b is the regression slope from the empirical relation, Δ is the slope of the saturation vapor pressure curve ($\text{Pa } ^\circ\text{C}^{-1}$), a is the regression intercept from the empirical relation, and Υ is the psychrometric constant ($\text{Pa } ^\circ\text{C}^{-1}$). This approach is quite appealing because of its simplicity and freedom from many sources of error inherent in a pure energy budget approach to calculating canopy and aerodynamic resistances.

The Appalachian region has hilly topography and a humid temperate climate. The region contains the headwaters of most major rivers of the Eastern USA. Agricultural production is frequently limited to pasture due to slope steepness, which limits vehicle access. There is merit in continually improving our ability to predict soil-water depletion by plants because of its impact on stream flow and forage yield. While canopy temperature measurements are useful to help monitor water use, they are seldom measured in this region.

The objective of this research was to determine the relation between canopy temperature and net radiation, vapor pressure deficit, and wind for a *Dactylis*

glomerata, L pasture under the humid, cloudy conditions characteristic of Appalachia

METHODS AND MATERIALS

This research was done at the USDA-ARS North Appalachian Experimental Watershed located at Coshocton, Ohio, latitude 40°22' N, longitude 81°47' W, and elevation 361 m The *Dactylis glomerata* L canopy measured was growing on a 1.8 m × 4.3 m × 2.5 m monolith lysimeter The soil was classified as a DeKalb silt loam, Typic Dystrochept (loamy-skeletal, mixed, mesic) The measurement period was from 20 April to 13 July 1989 (days of the year (DOY) 110–187) This period had frequent rainfall and the component of soil moisture considered available for plant extraction was never depleted by more than 25% Total soil moisture, monitored with a Troxler^a model 3322 neutron moisture gauge, was at no time depleted by more than 10%

The lysimeter was located on a 22% slope facing east It was located within a *D. glomerata* pasture grazed by cattle, except for a fenced exclusion area of 14.2 m × 16.6 m around the lysimeter All data were collected and stored using a Campbell Scientific CR7 datalogger^a The lysimeter's weight, measured with a Toledo^a scale, was recorded every 10 s for 2 min on the hour and averaged Percolation runoff were collected in large barrels and measured with FW-1 water-level recorders fitted with potentiometers to allow electronic measurement of float level

Precipitation was measured with a Belfort^a tipping bucket rain gauge and soil heat flux with two discs buried 2 cm below the soil surface The following sensors were placed 1 m above the canopy and adjusted weekly as needed Net radiation was measured with a Fritchen^a net radiometer mounted parallel to the slope, air temperature and humidity with a Campbell Scientific 207^a temperature and humidity probe, and wind with a Met One 014A^a wind speed sensor Canopy temperature was measured with an Everest 4001^a Infrared Temperature Transducer, with a 4° field of view, pointing north and 30° from horizontal, with the sensor shielded from direct solar radiation The measurement region was approximately 60 cm × 120 cm All climate parameters were stored as hourly averages from measurements taken every 10 s The calibrations for the infrared sensor and humidity probe were checked periodically and remained within specified tolerances throughout the period

Canopy temperature values were corrected for an assumed grass emissivity of 0.96

^aTrade names are included for the benefit of the reader, and do not imply endorsement or preferential treatment of the product by the authors or the USDA

RESULTS

On DOY 110 the vegetative canopy was about 20 cm tall and beginning its peak annual growth period. By DOY 140 it had reached its peak height of 75 cm (Fig 1(B)) and was beginning anthesis. Shortly thereafter, some of the heads began to lean, and during a couple of storms between DOY 163 and 168, the entire canopy lodged to about half of its previous height. On DOY 179 the grass was cut, chopped, and spread back on the lysimeter to conserve the nitrogen balance as part of another project. The ratio of evapotranspiration to net radiation for the rain-free days increased around DOY 136, when the weather became substantially warmer (Fig 1(A)). There was no apparent change in this ratio due to lodging of the canopy after DOY 162, however, the ratio did change after mowing on DOY 179.

Canopy temperature values for hours during which it rained or for hours during which net radiation was less than 100 W m^{-2} were not retained for the analysis. The data were segregated into periods containing about 50 sequential hourly measurement periods, collected over several days per period (Table 1). Multiple regression was used to statistically separate the effects of vapor pressure deficit, net radiation, and wind on the air-canopy temperature differential. Wind did not make a statistically significant contribution to the prediction of the air-canopy temperature differential for any of the 11 periods and is, therefore, not included in the regression statistics. This is consistent with results published by Merva and Fernandez (1985) showing that wind did not have a substantial impact on evapotranspiration under very humid conditions.

The air-canopy temperature differential was plotted against vapor pressure

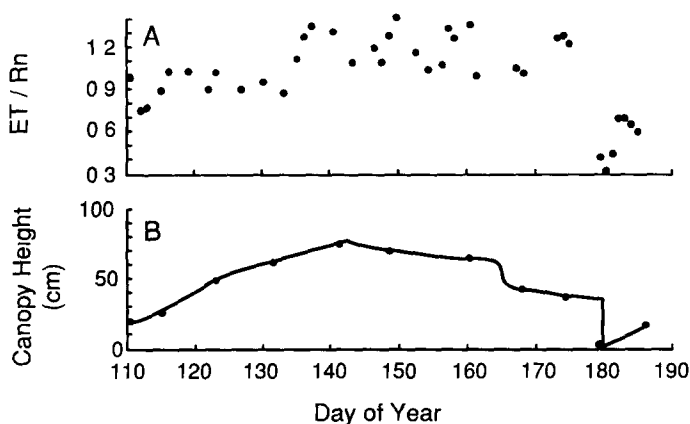


Fig 1 (A) Relative evapotranspiration (ET) for the period DOY 110–187. Relative ET is for days without rainfall and is expressed as the ratio of ET to net radiation. (B) Canopy height for the period DOY 110–187.

TABLE 1

Average and standard deviation of hourly air-canopy temperature differential (T_{a-c}), vapour pressure deficit (VPD), net radiation (R_n), wind, air temperature (T_a), along with regression statistics for the relation between air-canopy temperature differential and vapor pressure deficit, where a_1 is the slope and a_0 is the intercept, for the 11 time periods plotted in Fig. 2

Line	Period (DOY)	T_{a-c} (°C)		VPD (kPa)		R_n ($W m^{-2}$)		Wind ($m s^{-1}$)		T_a (°C)		Regression	
		Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	a_1	a_0 r^2
1	110-115	3.2	2.7	1.0	0.4	325	154	1.7	0.6	12.9	3.8	-3.60	6.9 0.95
2	116-123	0.9	1.6	0.9	0.6	297	160	1.9	0.5	16.6	4.9	-2.14	2.7 0.96
3	124-131	1.0	1.0	0.5	0.3	273	148	2.2	0.6	12.0	3.6	-2.11	2.1 0.74
4	132-139	-0.4	1.3	1.2	0.7	314	152	2.0	0.6	20.3	4.5	-1.85	1.9 0.84
5	140-147	-0.3	1.4	1.2	0.6	364	158	2.0	0.5	22.0	3.4	-2.06	2.2 0.86
6	148-152	0.1	1.3	1.2	0.4	352	147	2.1	0.5	24.2	4.3	-3.04	3.7 0.74
7	153-158	0.4	1.4	1.1	0.4	322	124	1.6	0.5	23.2	2.6	-2.59	3.3 0.80
8	159-167	1.1	1.0	0.8	0.4	267	153	1.7	0.6	20.9	2.9	-1.56	2.3 0.26
9	168-173	1.4	1.4	0.9	0.3	327	159	1.9	0.7	22.9	2.9	-1.66	2.9 0.70
10	174-178	1.3	1.5	1.6	0.5	382	147	1.4	0.4	29.3	2.0	-1.66	3.9 0.87
11	179-183	12.0	5.7	1.5	0.7	365	148	1.8	0.5	23.9	4.4	1.55	9.8 0.73

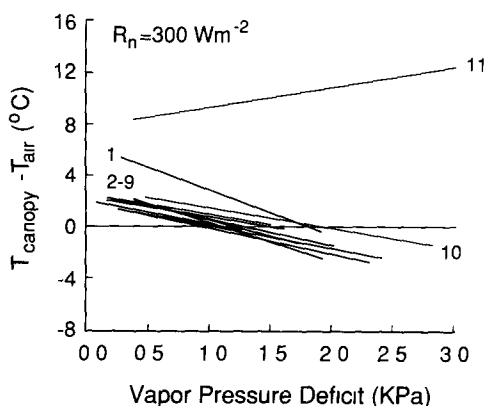


Fig 2 Air-canopy temperature differential as a function of vapor pressure deficit. The time period which each line represents along with its regression statistics is listed in Table 1.

deficit for the 11 sequential periods (Fig 2). The regression statistics, along with average climate parameters for the 11 periods are shown in Table 1. It is not clear why Period 8 had such a low r^2 , but the regression coefficients were not unusual. The lines in Fig 2 were normalized for an average net radiation of 300 W m^{-2} .

Data from the first period resulted in a line with a steeper slope and higher intercept than the next eight. This period had the lowest canopy biomass, since the grass was just beginning its peak growth period. The next eight periods all fall within a fairly tight region, and even the data from the tenth period after which the grass was lodged fell within the same region. The eleventh period, which was after the mowing, showed a distinctly different relationship than expected.

Since the forage canopy geometry was similar in appearance from DOY 120–162, a more detailed look was taken at this combined period. Hourly net radiation values showed a great deal of variability. Owing to rain and heavy cloud cover, 5 days had no hourly net radiation values over 100 W m^{-2} , and an additional 8 days had no values over 300 W m^{-2} . By contrast, only 19 days of the 43 days had any hours with average net radiation over 500 W m^{-2} , and 5 of those days only had 1 h with a value over that level.

With only 6 out of the 43 days during the period of peak dry matter accumulation having 4 or more hours with average net radiation greater than 500 W m^{-2} , canopy temperature can be routinely utilized only if values at low net radiation levels are readily interpreted. Data from the combined period were segregated by net radiation range, 100–200, 200–300, 300–400, 400–500, and over 500 W m^{-2} . The air-canopy temperature differential for each radiation level was plotted as a function of vapor pressure deficit (Fig 3), and the regression statistics listed in Table 2. The slopes of the five lines are

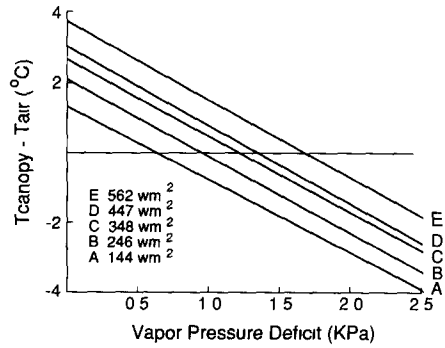


Fig 3 Air–canopy temperature differential as a function of vapor pressure deficit for the period DOY 120–162 split into the indicated five net solar radiation ranges The regression statistics for each line are listed in Table 2

virtually identical, indicating a decrease in canopy temperature of 2 1°C for each 1 kPa increase in vapor pressure deficit The correlation coefficients do not indicate that data from periods with low net radiation are inferior for predicting the slope of the relationship As expected, the intercept increased with net radiation level The increase in canopy temperature averaged 0 6°C for each 100 W m⁻² increase in net radiation This is quite similar to the 0 7°C increases for each 100 W m⁻² predicted, at a vapor pressure deficit of 1 5 kPa for alfalfa, by Hipps et al (1985)

Canopy and aerodynamic resistances, listed in Table 3, were calculated to give reference values for a fully developed orchardgrass canopy growing under conditions of a high level of available soil moisture for consecutive cloudy and sunny days The method of O’Toole and Real (1986) was used with one modification In eqn (4), the value of the air–canopy temperature differential extrapolated to a zero vapor pressure deficit (*a*), was replaced with the expression

$$a = (R_n - \bar{R}_n) \Delta a / \Delta R_n + \bar{a} \tag{6}$$

TABLE 2

Average net radiation and regression statistics, where *a*₁ is the slope and *a*₀ is the intercept, for the five net-radiation-dependent relationships between air–canopy temperature differential and vapor pressure deficit shown in Fig 3

<i>R_n</i> (W m ⁻²)	<i>a</i> ₁	<i>a</i> ₀	<i>r</i> ²
144	− 2 04	1 42	0 76
246	− 2 14	2 06	0 77
348	− 2 13	2 73	0 68
447	− 2 19	3 04	0 77
562	− 2 14	3 73	0 60

TABLE 3

Aerodynamic and canopy resistances calculated for orchardgrass transpiring at the potential rate with soil water non-limiting along with net radiation, vapor pressure deficit, wind, air temperature, canopy temperature, and soil heat flux for 2 consecutive days one cloudy and one sunny

Time	r_{ap} ($s\ m^{-1}$)	r_{cp} ($s\ m^{-1}$)	R_n ($W\ m^{-2}$)	VPD (kPa)	u ($m\ s^{-1}$)	T_a ($^{\circ}C$)	T_c ($^{\circ}C$)	S ($W\ m^{-2}$)
<i>Day 161</i>								
5 00	-87	-428	-7.4	0.27	1.4	12.7	10.6	-16.4
6 00	253	1242	2.9	0.30	1.5	12.8	11.1	-15.5
7 00	44	219	19.6	0.31	1.4	12.9	11.5	-14.2
8 00	19	94	66	0.32	1.6	13.3	12.4	-12.3
9 00	16.5	79	93	0.36	1.3	14.0	13.7	-10.3
10 00	15.2	73	112	0.38	1.6	14.5	14.1	-7.8
11 00	17.6	82	84	0.39	1.3	14.9	14.4	-6.1
12 00	15.8	74	107	0.40	1.3	15.4	15.3	-5.0
13 00	13.6	65	142	0.45	1.2	16.6	16.6	-3.2
14 00	13.7	61	175	0.49	1.6	17.4	17.0	-1.1
15 00	14.2	63	154	0.48	1.7	17.3	16.6	-0.6
16 00	16.8	75	100	0.46	1.6	16.8	15.8	-1.6
17 00	16.6	75	101	0.46	1.7	16.8	15.8	-2.4
18 00	21	95	63	0.46	1.2	16.6	15.3	-3.3
19 00	-27	-125	-20.7	0.50	1.2	16.6	13.1	-3.7
20 00	-40	-194	-14.2	0.40	1.1	14.8	12.5	-5.8
<i>Day 162</i>								
5 00	-18.6	-93	-25.8	0.25	1.2	12.4	8.8	-15.0
6 00	51	255	16.3	0.28	1.5	12.9	9.6	-14.2
7 00	13.8	65	148	0.39	0.9	15.4	13.1	-11.8
8 00	11.6	52	316	0.53	1.3	17.5	15.7	-7.2
9 00	11.4	48	452	0.72	1.0	19.7	18.4	-1.7
10 00	11.2	47	518	0.96	1.2	20.4	19.5	4.1
11 00	11.6	45	627	1.13	1.8	20.7	21.2	7.9
12 00	10.5	48	534	1.17	2.1	20.8	20.4	9.1
13 00	12.1	45	648	1.31	1.7	21.7	23.3	9.6
14 00	12.9	45	544	1.44	1.5	22.4	22.6	11.4
15 00	11.3	50	380	1.40	1.6	22.1	21.8	9.3
16 00	12.9	51	310	1.46	1.5	22.7	21.7	8.5
17 00	14.8	57	192	1.52	1.1	22.9	20.5	5.4
18 00	24.2	97	59	1.59	0.8	22.8	18.4	3.4
19 00	875	3695	0.9	1.36	0.6	21.4	16.1	1.8
20 00	-20.1	-91	-25.9	1.09	1.1	18.7	13.0	-1.6

which corrects for the change in intercept with solar radiation level R_n is the value of net radiation for the hourly calculation, \bar{R}_n is the average value of net radiation for the regression period, $\Delta a/\Delta R_n$ is the change in intercept with change in net radiation over the regression period, and \bar{a} is the average intercept for the regression period

Resistances calculated by this method appear to give reasonable results at

medium to high net radiation levels. However, at net radiation levels below 100 W m^{-2} , resistances increased substantially as net radiation decreased. While there may be some physical rationale for increases in canopy resistance as a result of decreases in stomatal aperture at low radiation levels, there is no physical reason for aerodynamic resistance to increase at constant wind levels. The fact that aerodynamic resistances do increase at low net radiation levels is a limitation of this calculation method. Future work will determine if this calculation method can successfully quantify pasture water stress at a wide range of net radiation levels.

DISCUSSION

Temperature regulates leaf biochemical process rates and influences disease and pest occurrence. Leaf temperature deviates from ambient air temperature in a manner dependent on solar radiation level and ambient vapor pressure deficit. The air-canopy temperature differential is also, to some degree, dependent on physical characteristics of the canopy such as height, structure, and density. The canopy temperature of physically similar forages may also differ in response owing to C3 and C4 photosynthetic pathway differences in stomata functioning (Feldhake and Boyer, 1985).

During late spring, the *D. glomerata* canopy lodged to about half of its peak height as a result of two severe storms. This did not result in a substantial change in canopy temperature or evapotranspiration relative to subsequent climate conditions. This is consistent with lush pasture having a large omega factor as described by Jarvis and McNaughton (1986). This means that since the canopy is poorly coupled aerodynamically to the atmosphere, evapotranspiration is driven primarily by net radiation, which would be little affected by lodging. Photosynthesis, however, is dependent on radiation distribution within the canopy in addition to intensity, and Turitzin and Drake (1981) measured a substantial decrease as a result of lodging.

This work establishes a baseline response of canopy temperature, and of canopy resistance calculated using canopy temperature, for *D. glomerata* pasture during spring. Canopy temperature decreased about 2.1°C for a 1 kPa decrease in ambient vapor pressure deficit regardless of whether solar radiation levels were consistently high or consistently low. Net radiation increased canopy temperature 0.6°C for each 100 W m^{-2} increase. These data may be useful for estimating canopy temperature at other times and locations, not only in response to daily differences in climate, but in response to differences in climate as a result of topographic position when soil moisture is not limiting.

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